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Measurements of four-lepton production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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ABSTRACT

The four-lepton (4ℓ , $\ell = e, \mu$) production cross section is measured in the mass range from 80 to 1000 GeV using 20.3 fb^{-1} of data in pp collisions at $\sqrt{s} = 8$ TeV collected with the ATLAS detector at the LHC. The 4ℓ events are produced in the decays of resonant Z and Higgs bosons and the non-resonant ZZ continuum originating from $q\bar{q}$, gg , and qg initial states. A total of 476 signal candidate events are observed with a background expectation of 26.2 ± 3.6 events, enabling the measurement of the integrated cross section and the differential cross section as a function of the invariant mass and transverse momentum of the four-lepton system.

In the mass range above 180 GeV, assuming the theoretical constraint on the $q\bar{q}$ production cross section calculated with perturbative NNLO QCD and NLO electroweak corrections, the signal strength of the gluon-fusion component relative to its leading-order prediction is determined to be $\mu_{gg} = 2.4 \pm 1.0$ (stat.) ± 0.5 (syst.) ± 0.8 (theory).

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1. Introduction

This paper presents measurements of the production of four isolated charged-leptons in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV using 20.3 fb^{-1} of data collected with the ATLAS detector at the LHC. For the four-lepton (4ℓ , $\ell = e, \mu$) production, both the integrated cross section and the differential cross sections as functions of invariant mass ($m_{4\ell}$) and transverse momentum ($p_T^{4\ell}$) of the 4ℓ system are measured in a mass range $80 < m_{4\ell} < 1000$ GeV. In addition, the 4ℓ signal strength of gluon fusion (ggF) production relative to its leading-order (LO) QCD estimate is measured. These measurements test the validity of the Standard Model (SM) through the interplay of QCD and electroweak effects for different 4ℓ production mechanisms as described by the LO Feynman diagrams shown in Fig. 1.

The 4ℓ signal events come from the decays of resonant Z and Higgs bosons and the non-resonant ZZ continuum produced from $q\bar{q}$, gg , and qg initial states, which are briefly discussed below.

• $q\bar{q}$ -initiated 4ℓ production

The tree-level diagrams for $q\bar{q} \rightarrow 4\ell$ production are shown in Fig. 1(a) and Fig. 1(b). The cross section as a function of $m_{4\ell}$ is shown in Fig. 2 (the dashed black histogram). The 4ℓ event production at the Z resonance occurs predominantly via the s -channel diagram as shown in Fig. 1(a), and was measured previously by

the ATLAS and CMS collaborations [1,2]. In the 4ℓ invariant mass region above the Z resonance the 4ℓ event production mainly proceeds through the t -channel process as shown in Fig. 1(b). The cross section significantly increases when both Z bosons are produced on-shell, resulting in a rise in the $m_{4\ell}$ spectrum around 180 GeV. In addition, a small portion of the 4ℓ events with the $q\bar{q}$ initial state can be produced from the vector-boson scattering (VBS) process.

• gg -initiated 4ℓ production

The LO diagrams of the Higgs-boson production and non-resonant 4ℓ production via ggF are shown in Fig. 1(c) and Fig. 1(d), respectively. The cross sections as a function of $m_{4\ell}$ are shown in Fig. 2 (the coloured histograms). The features of the 4ℓ events from the decays of Higgs-boson and continuum ZZ production via ggF are described below.

- (1) The dominant Higgs-boson production mechanism is ggF . Other Higgs-boson production mechanisms, vector-boson fusion (VBF), vector-boson associated production (VH), and top-pair associated production ($t\bar{t}H$), contribute less than 15% to the on-shell Higgs-boson decay to ZZ^* event rate. The on-shell Higgs-boson production and decay leads to a narrow resonance around 125 GeV, which has been a key signature in the Higgs-boson discovery by the ATLAS [3] and CMS [4] collaborations. The off-shell Higgs-boson production has a large destructive interference with continuum ZZ production from the ggF processes [5–7]. This effect can be observed in the

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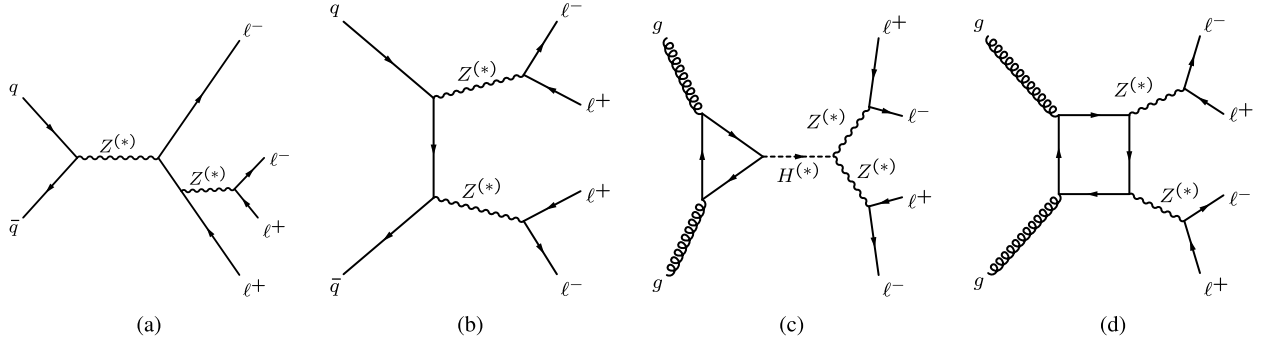


Fig. 1. The LO Feynman diagrams for the $q\bar{q}$ - and gg -initiated production of 4ℓ : (a) s -channel production of $q\bar{q} \rightarrow Z^{(*)} \rightarrow \ell^+\ell^-$ with associated radiative decays to an additional lepton pair; (b) t -channel production of $q\bar{q} \rightarrow Z^{(*)}Z^{(*)} \rightarrow 4\ell$; (c) Higgs-boson production through gluon fusion $gg \rightarrow H^{(*)} \rightarrow ZZ^{(*)} \rightarrow 4\ell$; (d) non-resonant 4ℓ production through the quark-box diagram $gg \rightarrow Z^{(*)}Z^{(*)} \rightarrow 4\ell$. The $Z^{(*)}$ notation stands for production of on- and off-shell Z bosons (Z and Z^*) and production of off-shell photons (γ^*).

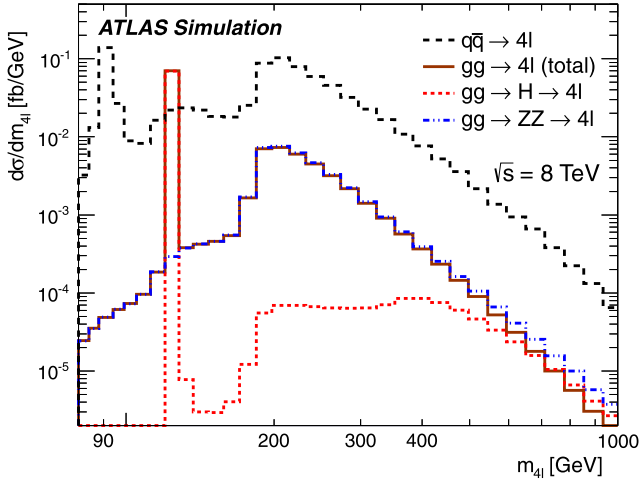


Fig. 2. The differential cross sections, $d\sigma/dm_{4\ell}$ versus the invariant mass of the four leptons $m_{4\ell}$, calculated by MCFM from the $q\bar{q}$ and gg initial states at $\sqrt{s} = 8$ TeV for the $2e2\mu$ final state in the experimental fiducial phase space (see Table 2 for definition). The inclusive $gg \rightarrow 4\ell$ distribution is the sum of the $gg \rightarrow H \rightarrow 4\ell$ and the $gg \rightarrow ZZ \rightarrow 4\ell$, and interference terms. The calculation of the $q\bar{q} \rightarrow 4\ell$ differential production cross section includes perturbative QCD corrections at NLO, while the distributions from the gg initial state are calculated at LO. The NNLO K -factors are applied to on-shell Higgs-boson production.

high-mass tail of the distributions shown in Fig. 2, and has been used as a tool to constrain the total Higgs-boson width by the ATLAS and CMS collaborations [8,9].

- (2) The non-resonant $ZZ \rightarrow 4\ell$ production via ggF, includes the production of off-shell Higgs bosons and continuum ZZ production as well as their interference. This process produces a sizeable number of 4ℓ events in the $m_{4\ell} > 2 \times m_Z$ mass region and dominates the total gg -initiated 4ℓ production.

Contributions from different processes have different strengths as a function of $m_{4\ell}$ (Fig. 2) and $p_T^{4\ell}$. Therefore, differential 4ℓ production cross sections are measured separately as a function of $m_{4\ell}$ and $p_T^{4\ell}$. The measurement of the integrated cross section is first performed in the experimental fiducial phase space, and then extended to a common phase space for three 4ℓ channels: $4e$, 4μ , and $2e2\mu$. This common phase space is defined by $80 < m_{4\ell} < 1000$ GeV, $m_{\ell\ell} > 4$ GeV, $p_T^{Z_{1,2}} > 2$ GeV, and the presence of four leptons each with $p_T > 5$ GeV and $|\eta| < 2.8$.

Currently, the gluon-fusion production is estimated theoretically with only a LO QCD approximation for the gg continuum production [6,10]. In this analysis the mass range above 180 GeV is used to determine the signal strength of the gluon-fusion com-

ponent with respect to its LO prediction. This is done by fitting the observed $m_{4\ell}$ spectrum using the next-to-next-to-leading-order (NNLO) QCD theoretical prediction, corrected for next-to-leading-order (NLO) electroweak effects, for the production originating from the $q\bar{q}$ initial state.

2. The ATLAS detector

The ATLAS detector [11] has a cylindrical geometry¹ and consists of an inner tracking detector (ID) surrounded by a 2 T superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) with a toroidal magnetic field. The ID provides tracking for charged particles for $|\eta| < 2.5$. It consists of silicon pixel and strip detectors surrounded by a straw tube tracker that also provides transition radiation measurements for electron identification. The electromagnetic and hadronic calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. For $|\eta| < 2.5$, the liquid-argon electromagnetic calorimeter is finely segmented and plays an important role in the electron identification. The MS includes fast trigger chambers ($|\eta| < 2.4$) and high-precision tracking chambers covering $|\eta| < 2.7$. A three-level trigger system selects events to be recorded for offline physics analysis.

3. Signal and background simulation

The signal modelling for $q\bar{q} \rightarrow 4\ell$ production uses the POWHEG-BOX Monte Carlo (MC) program [12–14], which includes perturbative QCD corrections at NLO. The production through the $q\bar{q}$ initial state is an NLO contribution to the $q\bar{q}$ process. The CT10NLO [15] set of parton distribution functions (PDFs), with QCD renormalisation and factorisation scales (μ_R, μ_F) set to $m_{4\ell}$ are used to calculate the cross section and generate the kinematic distributions. The NNLO QCD [16] and the NLO electroweak (EW) [17] corrections are applied to the NLO cross section calculated by POWHEG-BOX as a function of the 4ℓ mass for the kinematic region where both Z bosons are produced on-shell. Following the same approach as described in Ref. [8], the 4ℓ event distributions are re-weighted to match those expected when using QCD scales of $m_{4\ell}/2$. This is done to unify the QCD scales used in simulation of the $q\bar{q}$ and the gg processes.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln(\tan(\theta/2))$.

The signal modelling of the on-shell Higgs-boson production via the ggF and VBF mechanisms uses POWHEG-BOX which provides calculations at NLO QCD, with the CT10NLO PDFs and $\mu_R, \mu_F = m_{4\ell}$. The Higgs-boson production via the VH and $t\bar{t}H$ mechanisms is simulated with PYTHIA8 [18]. The NNLO QCD and NLO EW effects on the cross-section calculations for on-shell Higgs-boson production are summarised in Ref. [19]. The expected event yields of on-shell Higgs boson are normalised to the higher-order corrected cross sections.

The non-resonant 4ℓ signal production includes off-shell Higgs-boson production, continuum ZZ production, and their interference. The LO MCFM generator [20] is used to simulate the non-resonant ggF production, with the CT10NNLO [21] set of PDFs with QCD scales of μ_R, μ_F set to $m_{4\ell}/2$; while the LO MADGRAPH generator [22] is used to simulate non-resonant VBF and VBS production and their interference. The NNLO QCD corrections are available for off-shell Higgs-boson production [23] and for the interference between off-shell Higgs bosons and ZZ pairs from the gg initial state [24]. However, no higher-order corrections are available for the continuum $gg \rightarrow ZZ$ process, which dominates the 4ℓ events from the gg initial state in the region outside the Higgs-boson resonance. Therefore, the LO cross section is used for the normalisation of the 4ℓ events produced in gluon-fusion processes.

All the signal MC generators are interfaced to PYTHIA8 for parton shower simulation, except MADGRAPH, which is interfaced to PYTHIA6 [25].

Backgrounds in this analysis include reconstructed 4ℓ events from Z + jets, $t\bar{t}$, diboson ($ZW, Z\gamma$ and double Drell–Yan), triboson (VVV ($V = Z, W$), and VH ($H \rightarrow VV$), and Z + top ($t\bar{t}$ and t) processes, which are also simulated.

The reducible background from Z + jets production, which includes light- and heavy-flavour contributions, is modelled using both SHERPA [26] and ALPGEN [27]. The $Z\gamma$ process is simulated with SHERPA. The $t\bar{t}$ background is modelled using POWHEG-BOX.

Background events from ZH production, where $Z \rightarrow \ell\ell$ and $H \rightarrow VV$ ($VV = WW$ or ZZ with two leptons and two neutrinos or two leptons and two jets in the final state), are simulated with PYTHIA8. The ZW and the tZ processes are simulated with SHERPA and MADGRAPH, respectively. The irreducible background from VVV and $t\bar{t}Z$ is modelled with MADGRAPH. Finally, the double-Drell–Yan Z production is modelled with PYTHIA8.

For background modelling the POWHEG-BOX and MADGRAPH generators are interfaced to PYTHIA6 for the parton shower, hadronisation and underlying-event simulation. The ALPGEN generator is interfaced to HERWIG [28] for the parton shower and to JIMMY [29] for the underlying event simulation. SHERPA uses built-in models for both the parton shower and underlying-event description.

Both the signal and background MC events are simulated using the ATLAS detector simulation [30] based on the GEANT4 [31] framework. Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulations. The MC samples are re-weighted to reproduce the distribution of the mean number of interactions per bunch crossing observed in the data.

4. Event reconstruction and selection

The following event selection criteria are applied to the events collected with a single-lepton or dilepton trigger. The transverse momentum and transverse energy thresholds of the single-muon and single-electron triggers are 24 GeV. Two dimuon triggers are used, one with symmetric thresholds at 13 GeV and the other with asymmetric thresholds at 18 GeV and 8 GeV. For the dielectron trigger the symmetric thresholds are 12 GeV. Furthermore, there is

an electron–muon trigger of thresholds at 12 GeV (electron) and 8 GeV (muon).

A primary vertex reconstructed from at least three tracks, each with $p_T > 0.4$ GeV, is required. For events with more than one primary vertex, the vertex with the largest $\sum p_T^2$ of the associated tracks is selected.

Electron candidates are reconstructed from a combination of a cluster of energy deposits in the electromagnetic calorimeter and a track in the ID. They are required to have $p_T > 7$ GeV and $|\eta| < 2.47$. Candidate electrons must satisfy a loose set of identification criteria based on a likelihood built from parameters characterising the shower shape and track association as described in Ref. [32].

Muon identification is performed according to several criteria based on the information from the ID, the MS, and the calorimeter. The different types of reconstructed muons are: a) Combined (CB), which is the combination of tracks reconstructed independently in the ID and MS; b) Stand-Alone (SA), where the muon trajectory is reconstructed only in the MS; c) Segment-tagged (ST), where a track in the ID is associated with at least one local track segment in the MS; and d) Calorimeter-tagged (CaloTag), where a track in the ID is identified as a muon if it is associated with a minimum ionising particle's energy deposit in the calorimeter.

The acceptance for both the CB and ST muons is $|\eta| < 2.5$, while the SA muons are used to extend the $|\eta|$ acceptance to include the region from 2.5 to 2.7, which is not covered by the ID. CaloTag muons are used in the rapidity range $|\eta| < 0.1$ where there is incomplete MS coverage. All muon candidates are required to have $p_T > 6$ GeV.

In order to reject electrons and muons from hadron decays, only isolated leptons are selected. Two isolation requirements are used, one for the ID and one for the calorimeter. For the ID, the requirement is that the scalar sum of the transverse momenta, $\sum p_T$, of all tracks inside a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the lepton, excluding the lepton itself, be less than 15% of the lepton p_T . For the calorimeter, the $\sum E_T$ deposited inside a cone of $\Delta R = 0.2$ around the lepton, excluding the lepton itself and corrected for contributions from pile-up and, in the case of electrons, shower leakage, is required to be less than 30% of the muon p_T (15% for SA muons) and 20% of the electron E_T .

At the closest approach of a track to the primary vertex, the ratio of the transverse impact parameter d_0 to its uncertainty, the d_0 significance, must be smaller than 3.5 (6.5) for muons (electrons) to further reject leptons from heavy-flavour decays. The longitudinal impact parameter, $|z_0|$, must be less than 10 mm for electrons as well as muons (no vertex requirements are applied to SA muons).

Selection of lepton quadruplets is done separately in each of the channels $4\mu, 2e2\mu, 4e$, keeping only a single quadruplet per channel. Candidate quadruplets are formed by selecting two opposite-sign, same-flavour lepton pairs ($\ell^+\ell^-$). The two leading- p_T leptons of the quadruplet must have $p_T > 20$ and 15 GeV, respectively, while the third lepton must have $p_T > 10$ (8) GeV if it is an electron (muon). The four leptons of a quadruplet are required to be separated from each other by $\Delta R > 0.1$ (0.2) for same (different) flavour. At most one SA or a CaloTag muon is allowed in each quadruplet. The inclusion of final-state radiation to charged leptons follows the same approach as described in Ref. [33]. Each event is required to have the triggering lepton(s) matched to one or two of the selected leptons. All the selected 4ℓ events must lie in the $80 < m_{4\ell} < 1000$ GeV range.

For each channel, the lepton pair with the mass closest to the Z -boson mass is selected as the leading dilepton pair and its invariant mass, m_{12} , is required to be between 50 and 120 GeV. The sub-leading $\ell^+\ell^-$ pair with the largest invariant mass, m_{34} , among the remaining possible pairs, is selected in the invariant

mass range $12 < m_{34} < 120$ GeV. In the $4e$ and 4μ channels all possible $\ell^+\ell^-$ pairs are required to have $m_{\ell^+\ell^-} > 5$ GeV to reject events containing $J/\psi \rightarrow \ell^+\ell^-$ decays. The transverse momenta of the lepton pairs must be above 2 GeV.

5. Background estimation

The dominant reducible backgrounds for this analysis are from $Z + \text{jets}$ and $t\bar{t}$ processes and are estimated from data. Contributions from ZW , $Z\gamma$, tZ as well as from the irreducible backgrounds from $t\bar{t}Z$, VVV , ZH and double-DY processes are estimated from simulation.

The $Z + \text{jets}$ and $t\bar{t}$ backgrounds are estimated using two different final states in data: $\ell\ell + \mu\mu$ and $\ell\ell + ee$, where $\ell\ell$ ($\ell = e, \mu$) is the leading-lepton pair. The $\ell\ell + \mu\mu$ background arises from $Z + \text{jets}$ and $t\bar{t}$ processes where the $Z + \text{jets}$ contribution involves the associated production of a Z boson and heavy-flavour hadrons, which decay semileptonically, and a component arising from $Z + \text{light-flavour jets}$ with subsequent π/K in-flight decays. The background for $\ell\ell + ee$ final states arises from associated production of a Z boson with other objects namely jets misidentified as electrons, which can be light-flavour hadrons misidentified as electrons, photon conversions reconstructed as electrons, or electrons from semileptonic decays of heavy-flavour hadrons.

For both the $\ell\ell + \mu\mu$ and $\ell\ell + ee$ cases, the numbers of background events are estimated from a fit performed simultaneously to three mutually exclusive control regions, each of them providing information on one or more background components. The fit is based on the mass of the leading dilepton, m_{12} , which peaks at the Z mass for the $Z + \text{jets}$ component and has a broad distribution for the $t\bar{t}$ component. The three control regions are fit simultaneously to extract the different components of the reducible background, using a profile likelihood approach where the input template shapes for $Z + \text{jets}$ and $t\bar{t}$ are obtained from simulation. The fitted yields in the control regions are extrapolated to the signal region using efficiencies, referred to as transfer factors, obtained from simulation. Independent validation regions are used to check the extrapolations.

The three control regions for $\ell\ell + \mu\mu$ background are defined based on the impact parameter significance and isolation variables of the sub-leading muon pair and are constructed as follows:

- A heavy-flavour-enriched control region where at least one of the muons in the second pair fails the impact parameter significance requirement while the isolation requirement is relaxed;
- A light-flavour-enriched control region where at least one of the muons in the second pair fails the isolation requirement but passes the impact parameter significance cut;
- A $t\bar{t}$ -enriched region where the leading lepton pair is made of opposite-sign and different-flavour leptons. For the muons of the second pair there is no charge requirement, the isolation cut is relaxed and the muons must not satisfy the impact parameter requirement.

A validation region to check the $\ell\ell + \mu\mu$ background extrapolation is populated by both $Z + \text{jets}$ and $t\bar{t}$. The leading lepton pair is required to fulfil the full selection criteria, while there is neither isolation nor impact parameter requirements on the sub-leading muon pair. This region is used to check the fit results and verify that the data and MC simulation agree.

The three control regions for $\ell\ell + ee$ background are defined based on the impact parameter significance, isolation and electron identification requirements on the second electron pair. In all control regions at least one of the electrons in the second pair must

Table 1

Numbers of expected background events for different processes and channels.

| Process | $4e$ | 4μ | $2e2\mu$ |
|-------------------|-----------------|-----------------|-----------------|
| $t\bar{t}$ | 0.45 ± 0.24 | 0.68 ± 0.19 | 1.3 ± 0.5 |
| $Z + \text{jets}$ | 0.6 ± 0.29 | 5.3 ± 1.5 | 6.3 ± 1.4 |
| Diboson | 1.25 ± 0.18 | 0.83 ± 0.18 | 2.84 ± 0.34 |
| Triboson | 0.67 ± 0.12 | 0.97 ± 0.14 | 1.46 ± 0.19 |
| $Z + \text{top}$ | 0.62 ± 0.15 | 1.19 ± 0.32 | 1.7 ± 0.5 |

not satisfy the identification criteria. These regions are constructed as follows:

- A $Z + \text{jets}$ -enriched control region where at least one of the electrons of the second pair fails the track isolation and no calorimeter isolation is required;
- An additional $Z + \text{jets}$ -enriched control region where no charge requirement is made on the electrons of the second pair, while at least one of these electrons fails the impact parameter selection and no calorimeter or track isolation is required;
- A $t\bar{t}$ -enriched region, where the leading lepton pair is selected from opposite-sign and different-flavour leptons. There is no charge requirement for the sub-leading electron pair. At least one of the electrons of the second pair fails the calorimeter isolation requirement and neither track isolation nor impact parameter requirements are applied.

A validation region to check the $\ell\ell + ee$ background extrapolation is defined by removing the calorimeter isolation and requiring that at least one electron in the sub-leading pair fails the electron identification. Each candidate in the pair is required to pass the impact parameter and the track isolation selections. This region is used to check the fit outcome and verify that the data and MC simulation agree.

The residual contributions from ZZ and ZW production in all control regions are estimated from simulation. The purity of the $Z + \text{jets}$ and $t\bar{t}$ backgrounds in the control regions is above 95%.

In the validation regions, the post-fit MC predictions agree with the data within the statistical uncertainty.

The major uncertainties for the fitted reducible background come from the number of events in the control regions followed by the systematic uncertainty in the transfer factors. The latter is evaluated from the difference in the selection efficiency determined in data and simulation in dedicated control regions using leptons accompanying $Z \rightarrow \ell^+\ell^-$ candidates, where the leptons composing the Z -boson candidate are required to satisfy isolation and impact parameter criteria. Events with four leptons are excluded. For the MC estimated background the systematic uncertainties mainly come from theoretical cross-section uncertainties for different processes and from luminosity uncertainties in normalisations. The differential distributions for all background processes are taken from simulation.

The total number of background events estimated from data and MC simulation is 26.2 ± 3.6 . Numbers of background events expected per channel estimated for different processes are shown in Table 1. The background estimation was cross-checked with an alternative method, described in Refs. [1,34], called the fake-factor method. The results from this cross-check are found to be consistent within uncertainties with those described above.

6. Cross-section extraction method

Two cross sections are extracted from the number of observed events. One is the fiducial cross section, $\sigma_{4\ell}^{\text{fid}}$, in the experimental phase space defined by the event selection criteria and the other is the cross section, $\sigma_{4\ell}^{\text{ext}}$, in an extended common phase space

Table 2

List of selection cuts which define the fiducial region of the cross-section measurement. Same-flavour opposite-sign lepton pairs are denoted as SFOS, the leading lepton pair mass as m_{12} , and the sub-leading lepton pair mass as m_{34} . The four-momenta of all final-state photons within $\Delta R = 0.1$ of a lepton are added to the four-momentum of that lepton.

| | |
|---|--|
| Lepton selection | |
| Muons: | $p_T > 6 \text{ GeV}, \eta < 2.7$ |
| Electrons: | $p_T > 7 \text{ GeV}, \eta < 2.5$ |
| Lepton pairing | |
| Leading pair: | SFOS lepton pair with smallest $ m_{12} - m_{\ell\ell} $ |
| Sub-leading pair: | The remaining SFOS with the largest $m_{\ell\ell}$ |
| For both pairs: | $p_T^{\ell^+ \ell^-} > 2 \text{ GeV}$ |
| Event selection | |
| Lepton $p_T^{\ell_1, \ell_2, \ell_3}$: | $> 20, 15, 10 (8 \text{ if } \mu) \text{ GeV}$ |
| Mass requirements: | $50 < m_{12} < 120 \text{ GeV}$ $12 < m_{34} < 120 \text{ GeV}$ |
| Lepton separation: | $\Delta R(\ell_i, \ell_j) > 0.1 (0.2)$ for same- (different-) flavour leptons |
| J/ψ veto: | $m(\ell_i^+, \ell_j^-) > 5 \text{ GeV}$ |
| 4ℓ mass range: | $80 < m_{4\ell} < 1000 \text{ GeV}$ |

where electrons and muons have the same geometric and kinematic acceptance. The fiducial phase space is defined in Table 2. The extended phase space for the 4ℓ cross-section extraction is defined by $80 < m_{4\ell} < 1000 \text{ GeV}$, $m_{\ell^+\ell^-} > 4 \text{ GeV}$, $p_T^{Z_{1,2}} > 2 \text{ GeV}$, and the presence of four leptons each with $p_T > 5 \text{ GeV}$ and $|\eta| < 2.8$.

The cross section measurement is performed using a likelihood fit described below. For a given channel i , the observed number of events, N_{obs}^i , follows a Poisson distribution, $\text{Pois}(N_{\text{obs}}^i, N_{\text{pred}}^i)$, the mean of which, $N_{\text{pred}}^i = N_s^i + N_b^i$, is the sum of the expectations for signal and background yields. These yields depend on the fiducial cross section and the nuisance parameters, \vec{x} , which represent the experimental and theoretical uncertainties as:

$$N_s^i(\sigma_{4\ell}^{\text{fid}}, \vec{x}) = N_s^i(\sigma_{4\ell}^{\text{fid}}, 0) \left(1 + \sum_k x_k S_k^i\right), \quad (1)$$

$$N_b^i(\vec{x}) = N_b^i(0) \left(1 + \sum_k x_k B_k^i\right), \quad (2)$$

where S_k^i and B_k^i are the relative systematic effects on the signal and background, respectively, due to the k -th source of systematic uncertainty. The central expectation of the signal yield, corresponding to the systematic sources at the nominal value (referred to as the nuisance-free expectation), is given by:

$$N_s^i(\sigma_{4\ell}^{\text{fid}}, 0) = \mathcal{L} \cdot C_{4\ell} \cdot K_\tau \cdot \sigma_{4\ell}^{\text{fid}}, \quad (3)$$

where \mathcal{L} is the integrated luminosity, and $C_{4\ell}$ is the ratio of the number of accepted signal events to the number of generated events in the fiducial phase space. Corrections are applied to $C_{4\ell}$ to account for measured differences in trigger and reconstruction efficiencies between simulated and data samples. The $C_{4\ell}$ values are 53.3%, 82.2% and 67.7% for the $4e$, 4μ , and $2e2\mu$ channels, respectively. The contribution from τ -lepton decays is accounted for by a correction term $K_\tau = 1 + N_\tau^{\text{MC}}/N_{\text{sig}}^{\text{MC}}$, where N_τ^{MC} is the number of accepted simulated 4ℓ events in which at least one of the Z bosons decays into τ -lepton pairs, and $N_{\text{sig}}^{\text{MC}}$ is the number of accepted simulated ZZ events with decays into electrons or muons.

Cross-section measurements are extracted for a single channel or any combination of channels, using a likelihood method. The likelihood function is:

$$L(\sigma_{4\ell}^{\text{fid}}, \vec{x}) = \prod_i \text{Pois}(N_{\text{obs}}^i, N_{\text{pred}}^i(\sigma_{4\ell}^{\text{fid}}, \vec{x})) \cdot e^{-\frac{\vec{x}^2}{2}}, \quad (4)$$

Table 3

The combined relative uncertainties on the efficiency correction factor $C_{4\ell}$, evaluated as the sum in quadrature of the uncertainties from different sources, including electron and muon identification and theoretical uncertainties due to PDFs, QCD scales, and parton shower modelling. Extra uncertainties due to higher-order corrections for the gg process (NNLO K -factors for Higgs-boson production applied to the inclusive gg process) are also given.

| Sources | $\Delta C_{4\ell}/C_{4\ell}$ | | |
|------------------------|------------------------------|--------|----------|
| | $4e$ | 4μ | $2e2\mu$ |
| Experimental (e) | 4.8% | – | 2.3% |
| Experimental (μ) | – | 1.8% | 0.9% |
| Theoretical | 0.1% | 0.1% | 0.2% |
| Extra gg corrections | 0.6% | 0.2% | 0.3% |
| Combined uncertainty | 4.9% | 1.9% | 2.5% |

Table 4

Theoretical relative uncertainties on the fiducial acceptance $A_{4\ell}$ and $A_{4\ell} \times C_{4\ell}$ due to PDFs, QCD scales and parton shower modelling. Extra uncertainties due to higher-order corrections for the gg process (NNLO K -factors for Higgs-boson production applied to the inclusive gg process) are also given.

| Sources | $\Delta A_{4\ell}/A_{4\ell}$ | | |
|---|------------------------------|--------|----------|
| | $4e$ | 4μ | $2e2\mu$ |
| Theoretical | 1.2% | 1.0% | 1.6% |
| Extra gg corrections | 4.0% | 3.0% | 3.9% |
| $\Delta(A_{4\ell} \times C_{4\ell})/(A_{4\ell} \times C_{4\ell})$ | | | |
| Theoretical | 1.4% | 1.1% | 1.7% |
| Extra gg corrections | 4.6% | 3.2% | 4.2% |

where the product runs over the channels to be considered.

For the extended phase space the likelihood function is parameterised as a function of the extended cross section similar to the one shown in Eq. (3) and multiplied by the fiducial acceptance $A_{4\ell}$, which is the ratio of the number of events within the fiducial phase-space region to the total number of generated events in the extended phase space. The fiducial acceptance $A_{4\ell}$ is evaluated using simulation to be 41.6%, 50.3%, and 42.2%, for the $4e$, 4μ , and $2e2\mu$ channels, respectively. The differences are due to the electron and muon geometric detection coverage.

To find the central value of the cross section σ , the likelihood function is maximised simultaneously with respect to the nuisance parameters and σ . Correlations between the signal and background systematic uncertainties are taken into account in the likelihood fitting procedure.

7. Systematic uncertainties

Systematic uncertainties on the measurement arise from uncertainties on the integrated luminosity, the experimental calibrations of the lepton energy and momentum, and the lepton detection efficiencies, as well as the theoretical modelling of signal acceptance, and the background estimation. The overall uncertainty on the integrated luminosity is $\pm 2.8\%$, which is derived following the same methodology as that detailed in Ref. [35]. A summary of the relative uncertainties of $C_{4\ell}$, $A_{4\ell}$, and $A_{4\ell} \times C_{4\ell}$ is given in Tables 3 and 4.

The effect on the expected signal event yields due to experimental systematic uncertainties is determined from the uncertainties on lepton energy and momentum scales and resolutions, as well as the uncertainties on efficiencies of the lepton reconstruction and identification. The major contributions come from the uncertainties on lepton reconstruction and identification efficiencies [36–38].

The uncertainties on the signal acceptance for both $C_{4\ell}$ and $A_{4\ell}$ include theoretical uncertainties from the choice of QCD scales and PDF set. The scales are varied independently from 0.5 to 2.0 times

Table 5

Summary of the observed and predicted numbers of 4ℓ events in different 4ℓ channels. N^{Data} denotes the selected number of data candidates. $N^{\text{Total expected}}$ denotes the total predicted number of events (including τ contributions) for signal plus background. $N_{\text{non-gg}}^{\text{signal}}$ and the $N_{\text{gg}}^{\text{signal}}$ denote the predicted non-gg signal and the gg signal (no NNLO K -factor has been applied), respectively. N_{τ}^{MC} denotes the τ contributions. N_{bkg} denotes the total estimated number of background events (from data and MC simulation). The listed uncertainties of the expected number of signal events include statistical and experimental systematic uncertainties.

| Channel | N^{Data} | $N^{\text{Total expected}}$ | $N_{\text{non-gg}}^{\text{signal}}$ | $N_{\text{gg}}^{\text{signal}}$ | N_{τ}^{MC} | N_{bkg} |
|----------|-------------------|-----------------------------|-------------------------------------|---------------------------------|------------------------|------------------|
| $4e$ | 85 | 80 ± 4 | 68.4 ± 3.4 | 6.24 ± 0.31 | 1.28 ± 0.06 | 3.6 ± 0.5 |
| 4μ | 156 | 150.2 ± 2.9 | 128.2 ± 2.5 | 11.00 ± 0.21 | 2.18 ± 0.09 | 9.0 ± 1.5 |
| $2e2\mu$ | 235 | 205 ± 5 | 172 ± 5 | 16.0 ± 0.4 | 3.08 ± 0.13 | 13.6 ± 2.1 |
| Total | 476 | 435 ± 9 | 369 ± 9 | 33.3 ± 0.8 | 6.54 ± 0.14 | 26.2 ± 3.6 |

the nominal values of μ_R and μ_F . The PDFs uncertainties are estimated by using the envelope [39] of variations of different PDF sets, CT10, MSTW2008 [40] and NNPDF2.3 [41].

The $C_{4\ell}$ uncertainty is mostly experimental and of the order of 2–5%, while the $A_{4\ell}$ uncertainty is entirely theoretical and of the order of 3–5%. A range of values of the relative uncertainties on the $C_{4\ell}$ are given by 4.9%, 1.9%, and 2.5% for the $4e$, 4μ , and $2e2\mu$, respectively. The uncertainties on $C_{4\ell}$ due to higher-order corrections to the gg production processes are less than 0.6%. This is estimated by applying an approximate NNLO K -factor determined for the Higgs-boson production [23], assuming that it is applicable to the normalisation of the continuum $gg \rightarrow ZZ$ production cross section.

Uncertainties on $C_{4\ell}$, as a function of $m_{4\ell}$ and $p_T^{4\ell}$, are also computed for the differential cross section measurements. In the mass region ($m_{4\ell} < 150$ GeV), the relative uncertainties on $C_{4\ell}$ vary in the range of 4–9%, 1.7–2.7%, and 2–5% for the $4e$, 4μ , and $2e2\mu$ channel, respectively. In the mass region $m_{4\ell} > 150$ GeV, they are almost constant as a function of $m_{4\ell}$ and are about 4%, 1.8%, and 3% for the $4e$, 4μ , and $2e2\mu$ channel, respectively.

The relative uncertainties on $A_{4\ell}$ are 1.2%, 1.0%, and 1.6% for the $4e$, 4μ , and $2e2\mu$ channel, respectively, evaluated by comparing POWHEG-BOX and MCFM MC samples with the same approach for the QCD scales and the PDF uncertainties as described earlier. The QCD scale uncertainties do not change when going from NLO to NNLO for the signal normalisation for the $q\bar{q} \rightarrow 4\ell$ events [16]. An additional uncertainty (3–4%) is included in the $A_{4\ell}$ uncertainty estimate to account for the uncertainty of the Higgs-boson NNLO K -factor normalisation correction of the non-resonant 4ℓ signal from gluon fusion (labelled “extra gg corrections” in Tables 3 and 4).

The overall uncertainty on the background estimation is $\pm 14\%$. The contributions from different sources and channels are given in Table 1.

8. Results

8.1. Cross-section measurements

The numbers of expected and observed events after applying all selection criteria are shown in Table 5. A total of 476 candidate events is observed with a background expectation of 26.2 ± 3.6 events. The observed and predicted $m_{4\ell}$ and $p_T^{4\ell}$ distributions for the selected events are shown in Fig. 3.

The measured cross sections in the fiducial and extended phase space for different 4ℓ channels are summarised in Table 6 and compared to the SM predicted cross sections. The combined 4ℓ cross section in the extended phase space is found to be 73 ± 4 (stat.) ± 4 (syst.) ± 2 (lumi.) fb, compared to a SM prediction of 65 ± 4 fb. One should note that the cross section for non-resonant ZZ production from the gg-induced signal is only calculated at LO approximation, which could be significantly underestimated.

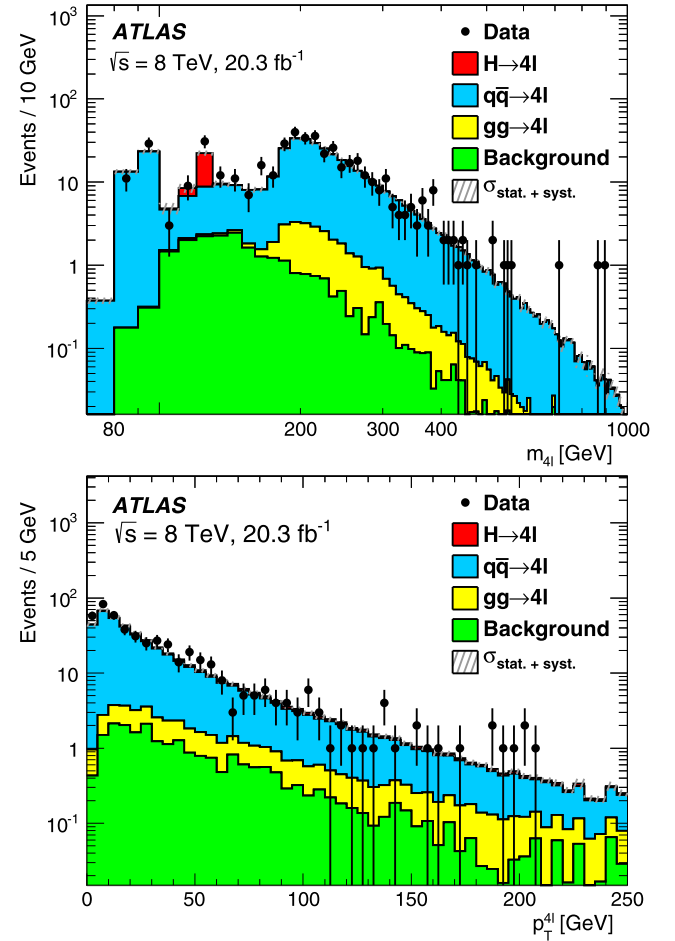


Fig. 3. Data and MC prediction comparison for selected events as a function of the invariant mass $m_{4\ell}$ (top) and the transverse momentum $p_T^{4\ell}$ (bottom) of the four-lepton system. The solid colours show the expected contributions from signal and background and the black points represent data with statistical error bars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

8.2. Differential cross-section measurement

The measurement of the differential cross-section is performed in the fiducial phase space defined in Table 2. The events from all three 4ℓ channels are combined into a common sample for the unfolding procedure. The unfolding is done as a function of the two kinematic variables $m_{4\ell}$ and $p_T^{4\ell}$. The $m_{4\ell}$ spectrum is essential for the study of the different production mechanisms, while the $p_T^{4\ell}$ spectrum is sensitive to higher-order QCD corrections and to QCD resummation effects at small $p_T^{4\ell}$ [10]. The high- $p_T^{4\ell}$ region is sensitive to top-loop effects in $gg \rightarrow H$ production as well as to anomalous triple-boson couplings.

Table 6
Measured cross sections in the fiducial phase space (σ^{fid}) and extended phase space (σ^{ext}), compared to their SM predictions (calculations described in Section 3). One should note that the non-resonant gg -induced signal cross section is only calculated at LO approximation.

| 4ℓ | Measured σ^{fid} [fb] | SM σ^{fid} [fb] | Measured σ^{ext} [fb] | SM σ^{ext} [fb] |
|----------|---|-------------------------------|---|-------------------------------|
| $4e$ | $7.4^{+0.9}_{-0.8} \text{ (stat)}^{+0.4}_{-0.3} \text{ (syst)}^{+0.2}_{-0.2} \text{ (lumi)}$ | 6.9 ± 0.4 | $17.8^{+2.1}_{-2.0} \text{ (stat)}^{+1.5}_{-1.1} \text{ (syst)}^{+0.5}_{-0.5} \text{ (lumi)}$ | 16.4 ± 1.0 |
| 4μ | $8.7^{+0.8}_{-0.7} \text{ (stat)}^{+0.2}_{-0.2} \text{ (syst)}^{+0.3}_{-0.2} \text{ (lumi)}$ | 8.3 ± 0.5 | $17.3^{+1.5}_{-1.4} \text{ (stat)}^{+0.9}_{-0.7} \text{ (syst)}^{+0.5}_{-0.5} \text{ (lumi)}$ | 16.4 ± 1.0 |
| $2e2\mu$ | $15.9^{+1.1}_{-1.1} \text{ (stat)}^{+0.5}_{-0.4} \text{ (syst)}^{+0.5}_{-0.4} \text{ (lumi)}$ | 13.7 ± 0.9 | $37.7^{+2.7}_{-2.6} \text{ (stat)}^{+2.5}_{-2.0} \text{ (syst)}^{+1.1}_{-1.1} \text{ (lumi)}$ | 32.1 ± 2.0 |
| Total | | | $73^{+4}_{-4} \text{ (stat)}^{+4}_{-4} \text{ (syst)}^{+2}_{-2} \text{ (lumi)}$ | 65 ± 4 |

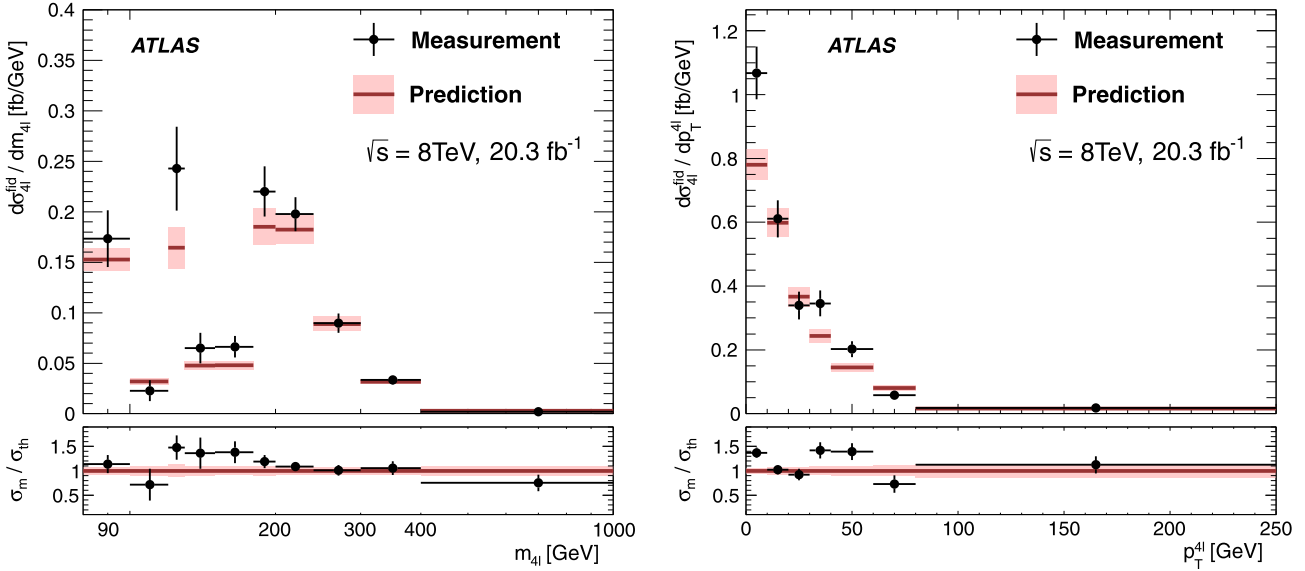


Fig. 4. The measured differential cross-section distributions (the black points) of $m_{4\ell}$ (left) and $p_T^{4\ell}$ (right), unfolded into the fiducial phase space, and compared to theory predictions (red histogram). The combined statistical and systematic uncertainties of the measurements are shown as the error bars of the unfolded spectra. The theoretical predictions are the sum of the differential cross sections of the $q\bar{q} \rightarrow 4\ell$ and $gg \rightarrow 4\ell$ processes, where the LO cross sections are used for the non-resonant gg -induced signals, and the cross sections of the on-shell Higgs boson and the $q\bar{q}$ production processes are corrected with the NNLO K -factors for the $m_{4\ell}$ spectrum; except for the $p_T^{4\ell}$ where only the NLO and LO predictions are used for the $q\bar{q}$ and the gg processes, respectively. The total theoretical uncertainties are shown as error bands evaluated by the sum in quadrature of the contributions from parton showers, QCD scales, PDF sets, and electroweak corrections. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The iterative Bayesian unfolding [42] is applied here. In the unfolding of binned data, the effects of the experimental acceptance and resolution are expressed in terms of a response matrix, where each element corresponds to the probability of an event in the i -th generator level bin being reconstructed in the j -th measurement bin. The response matrix is combined with the measured spectrum to form a likelihood, which is then multiplied by a prior distribution to produce the posterior probability of the true spectrum. The SM prediction is used as the initial prior, and once the posterior probability is obtained, it is used as the prior for the next iteration. The spectrum becomes insensitive to the initial prior after a few iterations. The differences between successive iterations are used to estimate the stability of the unfolding method. In this analysis four iterations are performed.

The unfolded distributions are shown in Fig. 4, where the differential cross section is presented as a function of $m_{4\ell}$ and $p_T^{4\ell}$ and compared to theory predictions. The data points shown in the figures are the measurements with combined statistical and systematic uncertainties. The theoretical predictions are the sum of the differential cross sections of the $q\bar{q} \rightarrow 4\ell$ and $gg \rightarrow 4\ell$ processes. The LO cross sections are used for the non-resonant gg -induced signals. The cross sections of the on-shell Higgs boson are normalised to include the NNLO QCD and NLO EW effects as summarised in Ref. [19]. The $q\bar{q}$ production processes are corrected with NNLO QCD and the NLO EW K -factors for the $m_{4\ell}$ spectrum

for $m_{4\ell} > 2 \times m_Z$. For the $p_T^{4\ell}$ spectrum, the $q\bar{q}$ signal prediction is calculated by POWHEG-BOX at NLO.

The uncertainties on the differential cross-section measurements are dominated by the statistical uncertainties of the data. For example, in the $m_{4\ell}$ regions between the Z and Higgs boson peaks and between the Higgs-boson mass m_H and $m_{4\ell} = 180$ GeV, the statistical uncertainties are of the order of 45% and 20%, respectively. In the high-mass region ($m_{4\ell} > 180$ GeV) they are of the order of 10%. Furthermore, one should note that the NNLO QCD corrections are not available for the $q\bar{q} \rightarrow 4\ell$ production calculation for the mass region $m_{4\ell} < 2 \times m_Z$.

In the $m_{4\ell}$ bin of 120–130 GeV, which is dominated by the resonant Higgs-boson contribution, the ratio of data to the MC prediction is compatible with the ATLAS measurement [33] of the Higgs-boson signal strength of $\mu_H = 1.44^{+0.40}_{-0.33}$. The data points in the $m_{4\ell}$ spectrum between 140 and 180 GeV are slightly more than 1σ above the theoretical predictions, where the NNLO QCD correction is not yet available. Some discrepancy is also observed in the lowest bin and in the region between 30 and 50 GeV of the $p_T^{4\ell}$ spectrum.

8.3. Extraction of the gg signal contribution in the $m_{4\ell} > 180$ GeV region

The extraction of the signal strength of the non-resonant $gg \rightarrow 4\ell$ production is performed in the high-mass region, $m_{4\ell} >$

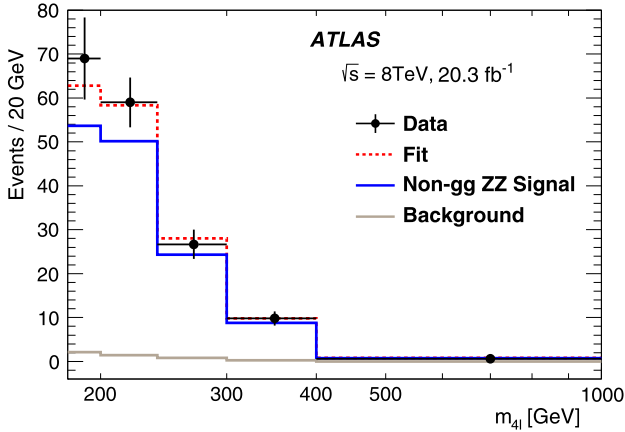


Fig. 5. Comparison of the $m_{4\ell}$ spectra between the data (black points with error bars) and the prediction (red histogram) after the likelihood fit of μ_{gg} . The non-gg signal from the theoretical prediction (blue histogram) and the background (brown histogram) are also shown. The gg contribution is the difference between data and the sum of the non-gg signal and the background. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

180 GeV, where this production mode is dominated by the continuum $gg \rightarrow ZZ$ process through a quark-box diagram intermediate state (see Fig. 1(d)). Additional contributions come from the off-shell Higgs-boson production and the interference between Higgs boson and continuum ZZ production.

The $m_{4\ell}$ spectrum is chosen as the discriminant to extract the gg signal strength with respect to the LO gg prediction: $\mu_{gg} = \sigma(\text{data})/\sigma(\text{LO})$.

The contribution of the $q\bar{q} \rightarrow ZZ$ production is constrained to the best theory knowledge (which accounts for QCD NNLO and EW NLO $m_{4\ell}$ -dependent corrections) and μ_{gg} is extracted from a likelihood fit using the reconstructed $m_{4\ell}$ distributions. The experimental uncertainties are treated as fully correlated between $q\bar{q}$ and gg processes. The theoretical uncertainties, including the uncertainties on the normalisation of the $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$, the shapes of 4ℓ spectra from both the $q\bar{q}$ and gg initial states, and the acceptance, are taken into account. The $m_{4\ell}$ distribution of the data, the fit, the expectation from non-gg signal processes and the background are shown in Fig. 5. The fit result is $\mu_{gg} = 2.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.8(\text{theory})$. This result corresponds to a gg-initiated cross section of 3.1 fb, which has the same relative uncertainties as μ_{gg} itself in the inclusive fiducial volume as defined in Table 2 with the additional requirement of $m_{4\ell} > 180$ GeV. The largest uncertainty is statistical. The theoretical uncertainty is mainly due to the normalisation uncertainty of the $q\bar{q} \rightarrow ZZ$ process.

The theoretical estimate of $m_{4\ell}$ -dependent K -factor for off-shell Higgs boson production given in Ref. [23] is in a range of 2.7–3.1 (with CT10NNLO PDF) and that given in Ref. [24] for the interference term is 2.05–2.45. These theoretical studies confirm that the gluon soft-collinear approximation predicts similar K -factors for off-shell Higgs-boson and interference, hence supporting the assumption of a similar K -factor for the continuum ZZ production. These theoretical calculated K -factors are compatible with the result obtained by this analysis, where the gg-initiated 4ℓ events are produced predominantly from the continuum ZZ production.

Applying the higher-order corrections to both the cross section of the off-shell Higgs-boson production and the contribution of the interference term, while keeping the LO cross section for the continuum $gg \rightarrow ZZ$ production, the change of the μ_{gg} fit result is negligible (approximately, $\Delta\mu_{gg} = 0.01$).

9. Conclusion

The measurement of four-lepton production in proton–proton collisions at $\sqrt{s} = 8$ TeV is presented using data corresponding to an integrated luminosity of 20.3 fb^{-1} collected with the ATLAS detector at the LHC. In total, 476 4ℓ candidate events are observed, with a background expectation of 26.2 ± 3.6 events, in the four-lepton invariant mass range between 80 and 1000 GeV. The 4ℓ production cross sections are determined in both fiducial and extended phase spaces. The measured cross section in the extended phase space, defined by $80 < m_{4\ell} < 1000$ GeV, $m_{\ell\ell} > 4$ GeV, $p_T^{Z_{1,2}} > 2$ GeV, four leptons each with $p_T > 5$ GeV and $|\eta| < 2.8$, is found to be 73 ± 4 (stat.) ± 4 (syst.) ± 2 (lumi.) fb, and is compared to a SM prediction of 65 ± 4 fb. The measurements of the 4ℓ differential cross sections are performed by unfolding the $m_{4\ell}$ and the $p_T^{4\ell}$ spectra. In the mass range above 180 GeV, assuming the theoretical constraint on the $q\bar{q}$ production cross section calculated with perturbative NNLO QCD and NLO electroweak corrections, the signal strength of the gluon-fusion component with respect to the LO prediction is determined to be $\mu_{gg} = 2.4 \pm 1.0$ (stat.) ± 0.5 (syst.) ± 0.8 (theory).

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